MINIMAL COST DESIGN OF VIRTUAL PRIVATE NETWORKS

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Abstract

The cost minimization of Virtual Private Networks (VPN) that use the resources of an underlying transport network is the key factor for their successful implementation [1]. The investigation in this paper is focused on 'network based VPNs', where the operation of the VPN is outsourced to an Internet Service Provider (ISP). The interest in such solutions is generated both by customers seeking to reduce support costs and by ISPs seeking new revenue sources. Solving the cost minimization would allow Internet Service Providers (ISP's) to define and deploy new VPN services. The basic building block of VPN is the tunnel. A tunnel operates as an overlay across the backbone, and the traffic sent through the tunnel is opaque to the underlying backbone. A VPN end point can terminate multiple tunnels or forward packets between different tunnels. Different tunnels can share the same physical link and traffic belonging to the same VPN tunnel can be carried along different physical links. The multiplexing and management of the VPN tunnels is made possible by core routers supporting the VPN of the underlying network.

The novelty of the presented work is the network flow model of VPN mapping on the underlying ISP network. We assume that the VPN topology, the topology of the ISP network and the total utilization cost for all underlying links are known parameters. Based on this, we propose a network management system based on a network flow optimization [2] in order to define the minimal cost link allocation for the VPN tunnels. We provide a simulation of the proposed optimal establishment of VPN tunnels and performance evaluation of the simulation results.

Keywords: *Virtual Private Networks (VPN), cost minimization, optimal network flow, tunneling in VPN.*

1. INTRODUCTION

VPN (Virtual Private Network) is the technology accepted by a number of vendors as their private networks grow within public network infrastructure. The end customers usually wish to access VPN by using Dial-up, ISDN, DSL, cable modems or dedicated private lines.

The growing interest in the use of VPNs pushes the search for more cost effective means of building and deploying private communication networks for multi-site communication than with existing approaches.

Today, there are several VPN approaches for building a VPN connectivity. Among the most popular cases are the Remote Access, Intranet and Extranet VPNs. Remote access VPNs are designed to support mobile workforce and telecommuters. End users can connect to their corporate Intranets through secure tunnels. Intranet VPNs connect business sites together. They are also known as Site-To-Site VPNs. Extranet VPNs allow business partners connect to the corporate site by limited authority.

Regarding the VPN implementation there are the following major approaches: Layer 2 based approach such as Frame Relay or ATM based VPN and Layer 3 based approach as MPLS (Multiple Protocol Label Switch) VPN and IP (Internet Protocol) VPN. Depending on different application scenarios they all have their own advantages and drawbacks. For instance, frame relay is inherently considered as secure [6] because of the fact that uses layer 2 technology but compared to IP VPN it is considerably more expensive. On the other hand, MPLS VPN is layer 3 based technology and therefore substantially more scalable. However, it requires all sites to be tied into the same service provider and does not lend itself to remote access from remote dialup users. IP VPN is cheaper, easy to build and have a clear advantage in remote access applications. Whereas, the latency of IP connections is being expected to improve.

In this paper we concentrate our attention on IP VPNs because their connectionless nature makes them more scalable and easier to build and manage than layer

2 based VPNs. Meanwhile, IP-VPNs provide the benefits of flexibility and simplicity in billing, management and provisioning as well as remote access beyond the service provider's network [3]. Regarding QoS in VPN, service classifications can be specified by policies implementation within the service provider's network.

The novelty of the presented work is the network flow model of VPN mapping on the underlying ISP network. We assume that the VPN topology, the topology of the ISP network and the total utilization cost for all underlying links are known parameters. Based on this, we propose a network management system based on a network flow optimization [2] in order to define the minimal cost link allocation for the VPN tunnels. We provide a simulation of the proposed optimal establishment of VPN tunnels and performance evaluation of the simulation results.

There are three major IP-VPN approaches [1],[3]: CPE-based VPN (Customer Premises Equipment VPN), CLE-based VPN [3](Customer located equipment VPN)[3] and network-based VPN [3], [1]. In CPE VPN, tunnels (virtual connections between end users) are established only between the CPE devices [5] and the service provider's routers are VPN-disabled. CLE VPN is based on equipment owned and operated by the service provider but located in the customer's premises [3]. While for network-based VPNs, the equipment is located in the service provider' premises at the edge of his network.

2. DESIGN OBJECTIVE

There is significant interest in network based VPN solutions, both by customers seeking to reduce support costs and by ISPs seeking new revenue sources. Supporting VPNs requires the use of particular mechanisms, which may lead to highly efficient and cost effective solutions, where common equipment and operations support are amortized across large numbers of customers [1]. This is the main reason we deal with Network based VPNs in this paper.

Our design objective is to minimize the cost of operation for a service provider supplying network-based IP-VPN solutions. In particular, from the tree basic types of service, mentioned in section 1 we will investigate Intranet VPNs, which enable secure site-to-site connection within the customer premises' environment.

3. NETWORK MODEL

We assume that IP-VPN is deployed to connect multiple enterprise sites, where each site has access to the nearest service provider point of presence (POP).

Site-to-site traffic is carried between POPs by secure links over the Internet or the service provider's backbone. A managed backbone network ensuring performance and reliability is required for IP-VPN to succeed as a WAN alternative technology. The VPN end users may choose ISDN, T1, T3 links etc., in order to get connected to the service provider. (See. Fig.1).

We further assume that we are dealing with small and medium business VPN customers establishing private tunnels between headquarter and company branches. Such topology is known as hub-and-spokes topology [3] shown in Fig.1. The bandwidth requirements for the VPN end users are given as traffic demand matrix and the price factors for the ISP we consider **leased line cost, maintenance and management** etc.

In order to achieve the design objective, we deploy the model, known as "multicommodity flow problem" (MFC). We consider the bandwidth, reserved over physical connections, for a certain VPN virtual connection, as commodity. In other words the individual commodities share common link capacities. First, we will present the MFC formulation and we will deploy it for simulation.

Legend:

—— T3 connection (Max43.23 Mbps with 28 T1
▬▬▬ OC3 connection (max.1.544 Mbps with 100 T1)

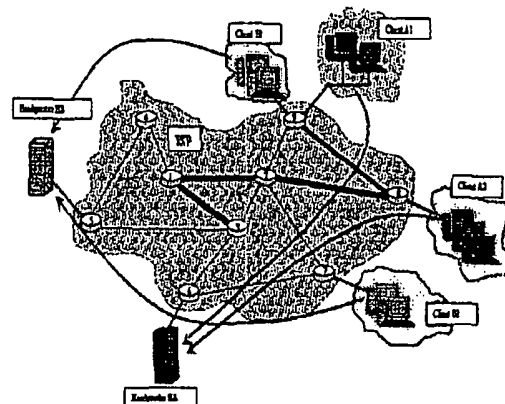Figure 1 Transport network and 2 VPNs

3.1. Min-Cost Multicommodity Flows Formulation

Given a directed graph $G(N,A)$ with n nodes and m arcs, and the set $K=(1,...,k)$, a multicommodity flow on G is a vector $x=[x^1,x^2,...,x^k]$ of h distinct flow vectors $x^h:A \rightarrow R^n$ where the index h is used to indicate different commodities. Let x^h_{ij} denote the flow of commodity h on arc (i,j) and c^h_{ij} per unit cost for commodity h on arc (i,j). Using this notation, we can formulate the Minimum cost multicommodity problem (MMFC) as follows [2]:

$$(MMCF) = \begin{cases} \min \sum_{h \in K} \sum_{(i,j) \in A} c^h_{ij} \cdot x^h_{ij} \\ \sum_{j:(i,j) \in A} x^h_{ij} - \sum_{j:(j,i) \in A} x^h_{ji} = b^h_i \qquad \forall i \in N, \forall h \in K \\ 0 \leq x^h_{ij} \leq u^h_{ij} \qquad \forall (i,j) \in A, \forall h \in K \\ \sum_{h \in K} x^h_{ij} \leq u_{ij} \qquad \forall (i,j) \in A \end{cases}$$

It requires the route of "commodities" on the G at minimal total cost, respecting the node balance constraints and individual (or single commodity) constraints $0 \leq x^h_{ij} \leq u^h_{ij}$ as well as mutual or aggregate capacity constraints $\sum_{h \in K} x^h_{ij} \leq u_{ij}$. After the formulation of MMCF we will reformulate the problem in order to match the network-based VPN design objective.

3.2. VPN Routing and Multicommodity Min-Cost Formulation

In order to adjust this formulation to the VPN network with near to real parameters formulation we make the following assumptions:

- The network links are bi-directional
- The VPN is given as demand traffic matrix
- The capacity of the physical links are limited by upper bound
- The Service Level Agreement between ISP and end-customer is the reserved bandwidth for the virtual connection.

The cost for the ISP for 1Mbps bandwidth using T3 links is $667 per month, while the cost for using OC3 is $267 per month [7]. We further assume in the example shown in Fig.1 that c^h_{jk} is the cost per unit bandwidth on link (i,j) for a virtual channel h, and x^h_{jk} is the reserved bandwidth (needs to compute it after solving the optimization). According to the notations for MMCF, u^h_{jk} is the maximum capacity, for a virtual link, and u_{jk} is the maximum capacity of a link between two VPN enabled routers (see Fig.1).

Then we formulate the routing problem as follows:

$$(MMCF) = \begin{cases} \min \sum_{h \in K} \sum_{(i,j) \in A} c^h_{ij} \cdot x^h_{ij} \qquad (1) \\ \sum_{j:(i,j) \in A} x^h_{ij} - \sum_{j:(j,i) \in A} x^h_{ji} = b^h_i \qquad \forall i \in N, \forall h \in K \qquad (2) \\ 0 \leq x^h_{ij} + x^h_{ji} \leq u^h_{ij} \qquad \forall (i,j) \in A, \forall h \in K \qquad (3) \\ \sum_{h \in K} x^h_{ij} + x^h_{ji} \leq u_{ij} \qquad \forall (i,j) \in A \qquad (4) \end{cases}$$

In this formulation, equation (1) is the LSP total transport cost for operating the network (satisfy VPN customer demands). Equation (2) is the flow balance equation for every node. Inequalities (3) and (4) are related to the bi-directionality of the physical links. They carry unidirectional virtual connections VC, but over one physical link it is possible to transport VC with different directions. The result of solving this optimization problem is the flow allocation x^h_{jk}. The allocation is the optimal routing - the amount of bandwidth, allocated for every virtual connection h on every physical link (i,j).

4. PERFORMANCE EVALUATION

The performance evaluation of the proposed novel routing algorithm is done by comparing it with QoS enabled OSPF routing. We made this choice due to the fact that the transport service provider operates in one domain. In such case, a widespread solution is to implement OSPF routing [9].

4.1. OSPF Algorithm overview

OSPF (Open Shortest Path First) is an industry standard protocol developed by the Internet Engineering Task Force (IETF). The basis of OSPF is the SPF (Shortest Path First) algorithm [8]. OSPF can function as a link state routing protocol and can also support the requirements of larger networks as well as multiple network layer protocols. OSPF is referred also as a distributed-database protocol. It maintains a topological database that stores information related to the state of links within an autonomous network and uses this information to calculate the shortest path [8]. We

implement this algorithm to compute the paths in the simulation network (See Fig.1).

4.2. Simulation of VPN Routing using Multicommodity MinCost Formulation and OSPF

SIMULATION A

The simulation is performed using the algebraic modeling language *OPL* and the Optimization tool CPLEX 7.0. The optical network shown in Fig.1 is taken as example. We assume there are two VPNs: VPN A and VPN B. VPN A has three nodes; A1 and A2 as clients and HA as headquarter. The same is valid for VPN B. The simulation computes the total transport cost for the service provider when satisfying the customer demands. It is assumed that when deploying a T3 link, the price for 1 Mb bandwidth is $267, while deploying an OC3 link the corresponding price is $667 (see Fig. 1). The routing problem we are faced with is on which links to reserve bandwidth in order to satisfy the customer's demands. We deploy two routing techniques: Open Shortest Path First (OSPF – see Section 4.1) and MinCost Multicommodity Flow Optimization (MMCF – see Section 3.2).

Table 1: Routing transport costs comparison deploying OSPF and MMCF for the network model shown in Fig.1

VPN A (Mbps)			VPN B (Mbps)			Total Cost in ($)		Savings (in %)
HQ A	A1	A2	HQ B	B1	B2	OSPF	MMCF	
10	5	5	5	3	2	28015	24956	
								10.92
8	3	5	4	1	3	22012	21353	
								2.99
13	10	3	15	5	10	54828	49109	
								10.43
12	2	10	8	3	5	36020	32695	
								9.23
20	10	10	15	5	10		59385	
								10.07
13	10	3	7	5	2	38820	34165	
								11.99
30	20	10	25	10	15	104060	94750	
								8.95
30	15	15	15	5	10	84045	75400	
								10.29
20	15	5	30	20	10	98050	86745	
								11.53
35	20	15	35	10	25		120770	
								6.68
40	20	20	40	16	24	146760	136652	
								6.89
42	20	22	40	22	18		138790	
								7.45
								Average 8.95

The VPN customer demands are between 0 and 43 Mbps, based on the fact that in the model network, the majority of the links are T3. The corresponding total transport costs are provided, along with the savings made when using MMCF. The graphical representation

of the simulation is given on Fig. 2. We can draw the following conclusions:

- For modest traffic load, the savings are relatively small, e.g. for demands: A1=3, A2=5, HQ A=8, B1=1, B2=3, HQ B=4 the transport cost savings are 2.99%.
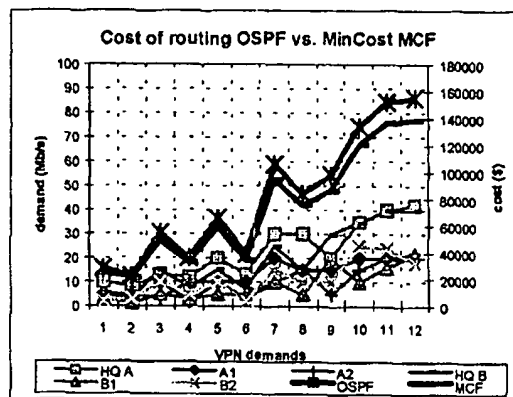- The deployment of MMCF is appropriate for higher traffic load.

Fig 2: Comparison of routing transport costs with OSPF and MMCF for the network model shown in Fig.1

SIMULATION B:

We examine different link capacities in order to estimate their influence on the performance improvement using MMCF. The difference between the network shown on Fig 1 and Fig 2 is that the link between nodes 8 and 9 is now T3 instead OC3.
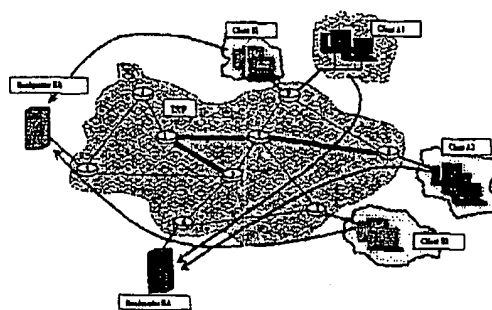

Fig. 3: Another network model. (Simulation B)

We perform the simulation using the same assumptions as in simulation A: we compare the total transport cost for satisfying customer bandwidth

demands for two VPNs using the OSPF and MMCF routing algorithms. The corresponding results are shown in Table 2 and in Fig.3:

Table 2: Routing transport costs comparison deploying OSPF and MMCF for the network model shown in Fig.3

VPN A (Mbps)			VPN B (Mbps)			Total Cost in ($)		Savings (in %)
HQ A	A1	A2	HQ B	B1	B2	OSPF	MMCF	
10	5	5	5	3	2	28015	26020	7.12
8	3	5	4	1	3	22012	20416	7.25
13	10	3	15	5	10	54828	51104	6.79
12	2	10	8	3	5	36020	33360	7.38
20	10	10	15	5	10	66035	61380	7.04
13	10	3	7	5	2	38820	36160	6.85
30	20	10	25	10	15	104060	98740	5.11
30	15	15	15	5	10	84045	70060	16.63
20	15	5	30	20	10	98050	91400	6.78
35	20	15	35	10	25	129415	124760	3.60
40	20	20	40	16	24	146760	141440	3.63
42	20	22	40	22	18	149962	144376	3.72
								Average 6.83

The results seem similar to those of simulation A. It can be seen that the savings are lower than those of simulation A: here the average operating saving is 6.83% compared to 8.95% we encountered in the previous simulation.
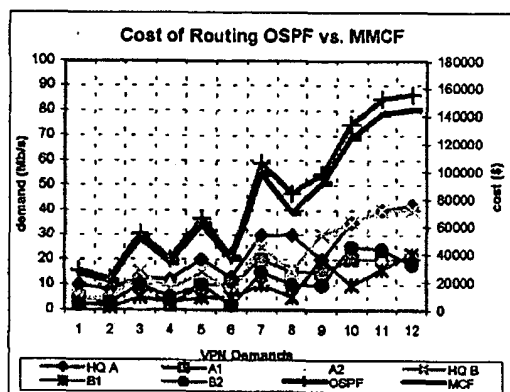

Fig 4: Comparison of routing transport costs with OSPF and MMCF for the network model shown in Fig.3

The results from Fig. 3 confirm our earlier conclusion. We can expect significant savings when

VPNs apply higher traffic loading levels to the underplaying ISP network.

SIMULATION C

In order to find the worst case MMCF performance, where the total transport cost of MinCost Multicommodity Flow Routing is equal to OSPF routing transport cost, we take into consideration the network topology depicted in Fig. 4.
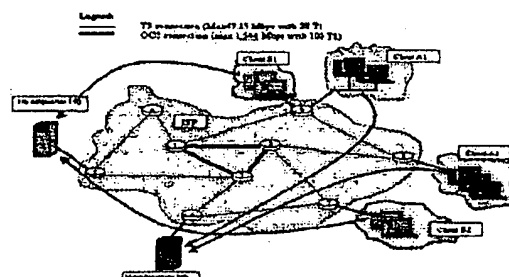

Fig.5: Network model for Simulation C.

The difference with the other topologies, shown in Fig.1 and Fig.3, is that the presented topology is "symmetric". While in Fig.1 we can identify linear high-speed OC-3 backbone, in Fig.5 the backbone is not as "asymmetric" as in Fig.1 and in Fig 3. The simulations, performed for this model are identical as the simulations for A and B: we compare the total cost savings of MMCF routing compared to OSPF routing. The results are listed in Table 3:

Table 3: Routing transport costs comparison deploying OSPF and MMCF for the network model shown in Fig.5

VPN A (Mbps)			VPN B (Mbps)			Total Cost in ($)		Savings (in %)
HQ A	A1	A2	HQ B	B1	B2	OSPF	MMCF	
10	5	5	5	3	2	24015	24015	0
8	3	5	4	1	3	19212	19212	0
13	10	3	15	5	10	44828	44828	0
12	2	10	8	3	5	32020	32020	0
20	10	10	15	5	10	56035	56035	0
13	10	3	7	5	2	32020	32020	0
30	20	10	25	10	15	88055	88055	0
30	15	15	15	5	10	72045	72045	0
20	15	5	30	20	10	80050	80050	0
35	20	15	35	10	25	112070	112070	0
40	20	20	40	16	24	128080	128080	0
42	20	22	40	22	18	131282	131282	0
								Average 0

We notice from the simulation that for the network from Fig. 5 the transport costs saving overall are equal to zero. In this case MMCF shows the same performance as OSPF. The reason for this is the symmetric structure of the network – if we take a closer look on Fig. 5 we notice that here the shortest paths (in hops) are the cheapest (with regard to total cost) paths. This is the "worst case" scenario for MMCF deployment.

5. CONCLUSIONS

We have proposed a Multicommodity Flow Optimization algorithm (MMFC) for resource allocation in network based IP virtual private networks. It is deployed by mapping the VPN topology on the underlying ISP network, casting it as a network flow model. Our design objective is to minimize the cost of operation for a service provider supplying network-based IP-VPN solutions. The novelty in this work is the total cost formulation as a part of the routing metrics and the influence of the network topology on the routing performance improvement. We assume that the Service Level Agreement between transport service providers and VPN customers guarantees the reserved bandwidth for the virtual connection. We compare the proposed MMFC routing with the widespread OSPF routing. We come to the following conclusions:

- The MMFC routing proves itself as cost-effective routing solution when the VPNs are placing high traffic volumes on the underlying transport network
- An "asymmetric" backbone transport network with regards to the backbone's topology and link speeds and prices is more appropriate for deploying MMFC routing.
- For a "symmetric" backbone transport network (e.g. ring) the MMFC routing is comparable or equal to OSPF routing.

Based on the fact that the ISP networks are getting more and more "meshed" and taking into consideration the highly competitive business environment the service providers are operating presently, we conclude that the proposed MMFC routing is a useful cost saving approach for VPN management and provisioning.

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